POWER UPGRADATION BY SIMULTANEOUS AC-DC POWER TRANSMISSION SYSTEM

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POWER UPGRADATION BY SIMULTANEOUS AC-DC POWER TRANSMISSION SYSTEM

A Thesis submitted in partial fulfilment of the requirements for the degree of Bachelor of Technology in "Electrical Engineering"

By

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ODISHA, INDIA

CERTIFICATE

This is to certify that the thesis entitled **“Power Upgradation by Simultaneous AC-DC Power Transmission System”** submitted by **Sidhartha Mohapatra (Roll no: 109EE0163)** in partial fulfilment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2012-2013 at National Institute of Technology, Rourkela is a bonafide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements.

The thesis, which is based on candidate’s own work, has not been submitted elsewhere for a degree or diploma.

In my opinion, the draft report/thesis is of standard required for the award of **Bachelor of Technology** in **Electrical Engineering.**

Place: Rourkela

Department of Electrical Engineering **Prof. P.C.Panda**

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Sidhartha Mohapatra (109EE0163)

B. Tech. (Electrical Engineering)

ABSTRACT

Due to increasing power demand there are huge requirements for construction of new transmission lines. But ROW (Right of Way) problems are hindering the erection of transmission lines. So instead of erecting new lines the existing AC lines are modified to simultaneous AC-DC lines to increase their power transfer capability close to their thermal limits. This thesis presents the method to convert an existing double circuit EHVAC line into a simultaneous AC-DC transmission line. A triple circuit ac transmission line is compared with a simultaneous AC-DC line. Both the systems are studied and transmission angle of double circuit line is varied up to 80^0 which is generally not possible for a pure ac line. Sending end power, receiving end power and transmission losses of both the systems are found out and percentage power upgradation is calculated. Simulation is carried out using MATLAB/SIMULINK.

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CHAPTER 1

INTRODUCTION

I. INTRODUCTION

In recent years, the problem of right-of-ways (ROW) is a major concern. Countries are experiencing increasing difficulties in finding suitable paths for erecting new overhead transmission lines in order to meet the increasing power demand due to rapid urbanization and industrialization. There is huge pressure to provide the substantial power upgrading of existing AC transmission line corridors. Two possible suggestions discussed are:

- Appropriate modification to existing ac lines without major new construction with increased voltage level either AC or DC.
- Eliminating HV/EHV ac lines and their substitution with new lines of EHV/UHV AC or HVDC.

In the first option though we can transmit more power with increased transmission voltage and minimize transmission losses but it will lead to more insulation cost and subsequently clearance required will be more. This will add to insulation cost and cost of erection of transmission towers. In the second option though we can transmit more power through new EHV/UHV lines employing FACTS devices but transmission angle is generally less than 30^0 as sufficient margin is kept against major disturbances like tripping of a major feeder, a three phase fault etc in order to achieve transient stability. As a result, the loading of the lines is much less than their thermal limits. Recently proposed concept of simultaneous ac-dc power transmission enables the long EHV ac lines to be loaded close to their thermal limits. The progress in the field of power electronics has influenced the power industry very much and the emergence of FACTS devices is the outcome we can see. Very fast controls of SCRs in FACTS devices like Static VAR System (SVS), Controlled Series Capacitor (CSC), and Static Phase Shifter (SPS) and controlled Braking Resistors improve stability and damp out oscillations in Power Systems. The HVDC with classical DC power control even with supplementary damping signal does not contribute to system synchronizing torque and may increase the risk of instability. So HVDC lines in parallel with EHVAC lines are recommended to improve transient and small signal stability of power system. Advanced HVDC large signal stabilizing control strategies can be developed to produce large amount of synchronizing and damping torques that can effectively stabilize the AC system and damp out all power oscillations on the parallel AC transmission after faults. Such controls also optimize the use of the HVDC short-term overload capacity without need for additional reactive power support. The increase in parallel AC transmission transient stability MW transfer limit can almost be equal to the HVDC temporary overload. The transmission angle can be as high as 80^0 as transient stability is greatly enhanced by rapidly modulating dc power. These features constitute large savings compared to conventional solutions.

In this project, a single machine infinite bus (SMIB) connected by a double circuit AC line; modified to simultaneous AC–DC power transmission has been taken up for study. For the purpose of comparison, a triple circuit line with pure AC transmission was also studied. The transmission angle is varied up to 80^0 in case of simultaneous AC-DC Power Transmission System. Such a large angle is not possible in pure AC systems. Sending end power, receiving end power and transmission losses were calculated for both the configurations and percentage power upgradation was calculated finally. The systems were studied using SIMULINK.

CHAPTER 2

BACKGROUND AND

LITERATURE SURVEY

II. BACKGROUND AND LITERATURE SURVEY

The flexible ac transmission system (FACTS) devices are the outcomes of power electronics technology. They improve stability to achieve bulk transmission of power.

Another way by is by using simultaneous ac–dc power transmission in which the transmission lines carry dc current superimposed on ac current. Addition of the dc power improves the stability and both ac and dc power flow independently.

Earlier it was proposed that a single circuit ac line is superimposed on a unipolar dc link with ground as return path. The limitations of ground as return path are corrosion of any metallic material if it comes in its path, interference with neighbouring communication circuits and dangerous step and touch potentials. The conductor voltages with respect to ground also become higher due to addition of dc voltage; hence more discs have to be added in each insulator string to provide proper insulation. The phase-to-phase clearance was kept constant, as the line-to-line voltage remains same.

Our approach is to show that the power upgradation is achieved without any alteration in the existing EHV ac line. The objective is to utilize the advantage of composite ac–dc transmission by loading the line close to its upper thermal limit.

2.1 THEORY OF SIMULTANEOUS AC-DC TRANSMISSION

Fig. 1 shows the basic model for composite ac-dc power flow through a double circuit ac transmission line. Line commutated 12-pulse bridge rectifier is used and the dc power is injected into the neutral point of the zigzag connected secondary of sending end transformer and is regained to ac by the line commutated 12-pulse bridge inverter at the receiving end side which is also connected to the neutral of zigzag connected winding of the receiving end transformer. The double circuit ac line carriers both ac power and dc power. The dc current flows through the rectifier and the inverter and gets equally divided in all the three conductors of the three phases as resistances of the three conductors are approximately equal.

The conductors of the second transmission line act as the return path for the dc current. The saturation of transformer due to flow of dc current can be avoided by using zigzag connected winding at both ends. The windings of zigzag transformer are differentially connected. The fluxes produced by the dc current ($\frac{I_d}{3}$) flowing through each winding of the core of a zigzag transformer have equal magnitude and opposite in direction and hence cancel each other so that the net dc flux becomes zero. Thus, the saturation of the core due to dc current is removed. A series reactor X_d is used to reduce ripples in dc current. It also reduces the rate of rise of fault current thus allowing sufficient time for the circuit breakers to operate. The triplen harmonics and zero sequence components of currents are also greatly suppressed by the presence of series reactor.

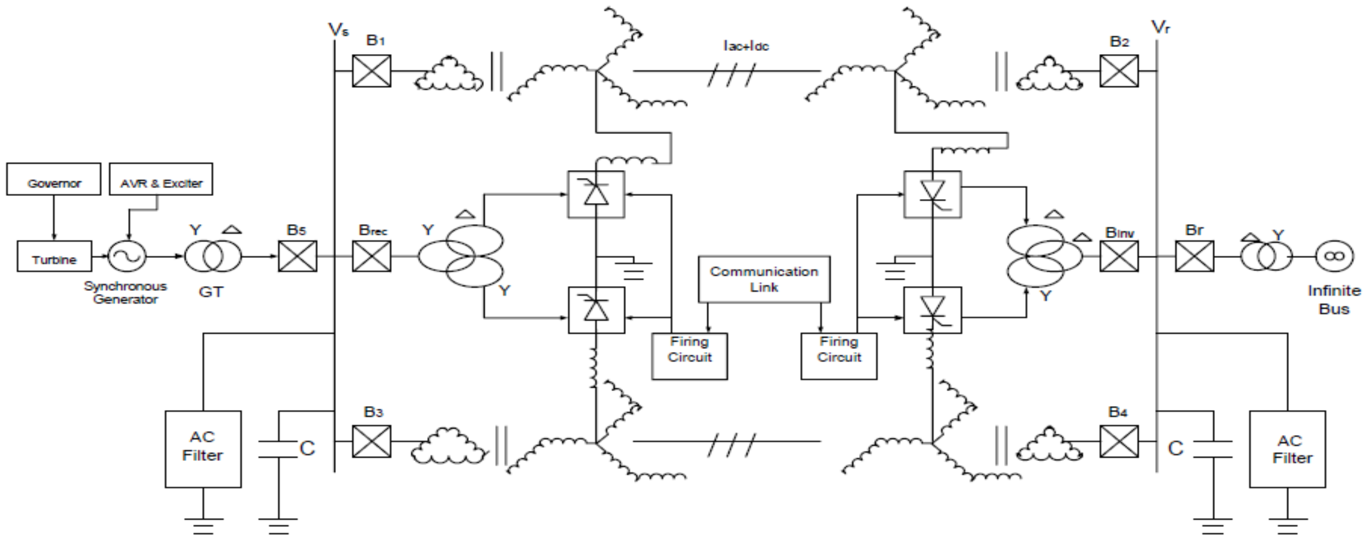


Figure 1: Model for simultaneous AC-DC Transmission

The rectifier operates under CC (Constant Current) control and the inverter operates under CEA (Constant Extinction Angle) control. So the equivalent circuit of the model considering single ac line under steady-state operating conditions and approximating the distributed line as a lumped π network is given in Figure 2.

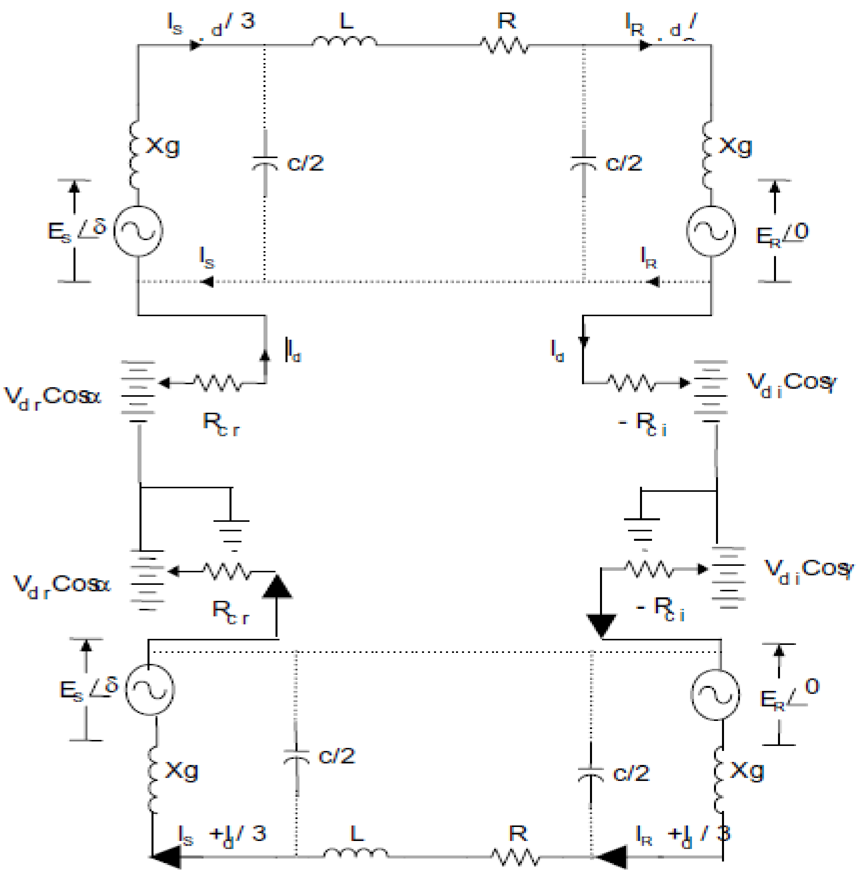


Figure 2: Equivalent Circuit Diagram

The ac current return path is shown by dotted lines in the figure. The second transmission line provides return path for dc current, and each conductor of the line carries ($\frac{I_d}{3}$) along with the ac current per phase and the maximum values of rectifier and inverter side dc voltages are V_{dro} and V_{dio} respectively. R_{cr} and R_{ci} are the commutating resistances of the rectifier and the inverter respectively, and α is the firing angle and γ is the extinction angle of the rectifier and the inverter respectively.

2.2 EQUATIONS

Let I_{dc} be the DC link current, R_{cr} and R_{ci} be the commutation resistances of the rectifier and the inverter respectively. Let α be the ignition angle of the rectifier and γ be the extinction angle of the inverter. Let $P_{d\_rectifier}$ = Rectifier end DC power, $P_{d\_inverter}$ = Inverter end DC power. Let R_{dc} be the dc link resistance. Let $V_{d\_rectifier}$ = Rectifier terminal voltage, $V_{d\_inverter}$ = Inverter terminal voltage

$$I_{dc} = [V_{dro} \cos\alpha - V_{dio} \cos\gamma] / [R_{cr} + R_{dc} - R_{ci}] \quad (2.2.1)$$

$$P_{d\_rectifier} = V_{d\_rectifier} \times I_{dc} \quad (2.2.2)$$

$$P_{d\_inverter} = V_{d\_inverter} \times I_{dc} \quad (2.2.3)$$

Reactive powers required by the rectifier and the inverter are:

$$Q_{d\_rectifier} = P_{d\_rectifier} \times \tan(\theta_{rectifier}) \quad (2.2.4)$$

$$Q_{d\_inverter} = P_{d\_inverter} \times \tan(\theta_{inverter}) \quad (2.2.5)$$

Where

$$\cos(\theta_{rectifier}) = \frac{V_{d\_rectifier}}{V_{dro}} = [\cos\alpha + \cos(\alpha + \mu_{rectifier})] / 2 \quad (2.2.6)$$

$$\cos(\theta_{inverter}) = \frac{V_{d\_inverter}}{V_{dio}} = [\cos\gamma + \cos(\gamma + \mu_{inverter})] / 2 \quad (2.2.7)$$

$\mu_{rectifier}$ is the overlap angle of the rectifier and $\mu_{inverter}$ is the overlap angle of the inverter respectively and the total active and reactive power at the both ends are:

$$P_{total\_sending\_end} = P_{s\_ac} + P_{d\_rectifier} \text{ and } P_{total\_receiving\_end} = P_{r\_ac} + P_{d\_inverter} \quad (2.2.8)$$

$$Q_{total\_sending\_end} = Q_{s\_ac} + Q_{d\_rectifier} \text{ and } Q_{total\_receiving\_end} = Q_{r\_ac} + Q_{d\_inverter} \quad (2.2.9)$$

Where P_{s_ac}, Q_{s_ac} = Sending end ac power and P_{r_ac}, Q_{r_ac} = Receiving end ac power

Total transmission loss:

$$P_{loss} = P_{total\_sending\_end} - P_{total\_receiving\_end} \quad (2.2.10)$$

Let I_{ac} be the rms ac current per phase of the line. Then total rms current I_{total} through any conductor is

$$I_{total} = \sqrt{{I_{ac}}^2 + \left(\frac{I_{dc}}{3}\right)^2} \quad (2.2.11)$$

The total current I through the conductors is` not symmetrical but the two original zero-crossings in each one cycle in current wave are possessed for (I_{dc} / $3I_{ac}$) <$\sqrt{2}$.

The phase to ground voltage can be written as the dc voltage V_{dc} with a composition of sinusoidally varying ac voltages V_{ac} and the peak value being:

$$V_{max} = V_{dc} + \sqrt{2}\, V_{ac} \qquad (2.2.12)$$

Electric field of the simultaneous AC-DC line consists of the field produced by the dc voltage as well as ac voltage creating a superimposed effect of electric fields. It is seen that the sudden changes in electric field polarity occurs and it changes its sign twice in a single cycle if $\left(\frac{V_{dc}}{V_{ac}}\right) < \sqrt{2}$. Therefore, higher creepage distances for insulator discs used in HVDC lines are avoided.

Each conductor has to be insulated for the maximum V_{max} but the fact is line to line voltage has no component of dc voltages and $V_{LL\,(max)}$ = 2.45 V_{ac}. Therefore, we come to the conclusion that conductor to conductor separated distance is found out only by ac voltage of the line in lieu of the total superimposed one.

Assuming (V_{dc} / V_{ac}) = k

$$P_{dc\_power} / P_{ac\_power} = (V_{dc} \times I_{dc}) / (3 \times V_{ac} \times I_{ac} \times \cos\theta) = (k \times \sqrt{1 - X^2})/(X \times \cos\theta) \qquad (2.2.13)$$

Total Power

$$P_{total} = P_{dc\_power} + P_{ac\_power} = [1 + (k \times \sqrt{1 - X^2})/(X \times \cos\theta)] \times P_{ac\_power} \qquad (2.2.14)$$

Here preliminary techniques used for analysis of a HVDC system have been adopted. Different values of ac filters and dc filters are used in HVDC system and these are connected to the primary sides of the rectifier and inverter transformer respectively to filter out higher harmonics that is (n*p±1)th order on ac sides and the (n*p)th order on dc sides. Besides, filters can be omitted for very low values of V_{dc} and I_{dc}. Here neutral of the zigzag transformer at dc potential. So it has to be properly insulated. Conventional cvts are used in EHV ac lines to measure stepped down ac component of transmission line voltage. The composite ac-dc voltage in the transmission line does not affect the working of cvts. Linear couplers that has high air-gap core may be used for measuring ac component of line current as the dc component of line current cannot saturate high air-gap cores.

2.3 POWER UPGRADATION OF EHV AC TRANSMISSION LINE BY SIMULTANEOUS AC-DC TRANSMISSION

The total power transfer through the dual circuit line before conversion

$$P_{transfer} = 3\, V_{ac}^{2} \sin \delta_1 / X \tag{2.3.1}$$

X is the transfer reactance per phase of the double circuit line (or of single circuit line if considered for conversion) and δ_1 is the power angle between the voltages at the two ends. To keep sufficient margin against transient instability, δ_1 is generally kept low and its value seldom exceeds 30^0. With the increasing length of line the loadability of the line decreases. An approximate value of δ_1 may be computed from the load ability curve by knowing the SIL (Surge Impedance Loading) and transfer reactance of the line X.

$$P_{transfer} = 2\times M\times SIL \tag{2.3.2}$$

Where M is the multiplying factor and its value decreases with increasing length of the line. The value of M can be obtained from the loadability curve. The total power through composite AC-DC transmission line is

$$P_{total} = P_{ac\_power} + P_{dc\_power} = 3\, V_{ac}^{2} \sin \delta_2 / X + 2V_{dc}\times I_{dc} \tag{2.3.3}$$

The power angle δ can be enhanced to a very high value due to fast controllability and modulation of the DC power. For a constant value of total power P_{dc} can be modulated by fast control of current controllers of DC power converters.

Rough value of AC current per phase per circuit of the double circuit line can be computed as:

$$I_{ac} = (V_{ac} \sin \tfrac{\delta}{2}) / X \tag{2.3.4}$$

Power up gradation in percentage or increase in power transfer capability of the composite AC-DC transmission line is:

$$\text{Power up Gradation} = \frac{\text{Power transfer by composite AC}-\text{DC line}-\text{Power transfer by pure AC line}}{\text{Power transfer by pure AC line}}$$

$$\%\ \text{Power up Gradation} = \frac{P_t - P_{total}}{P_{total}} \times 100 \tag{2.3.5}$$

CHAPTER 3

PROPOSED SIMULINK MODEL

III.SIMULINK MODELS

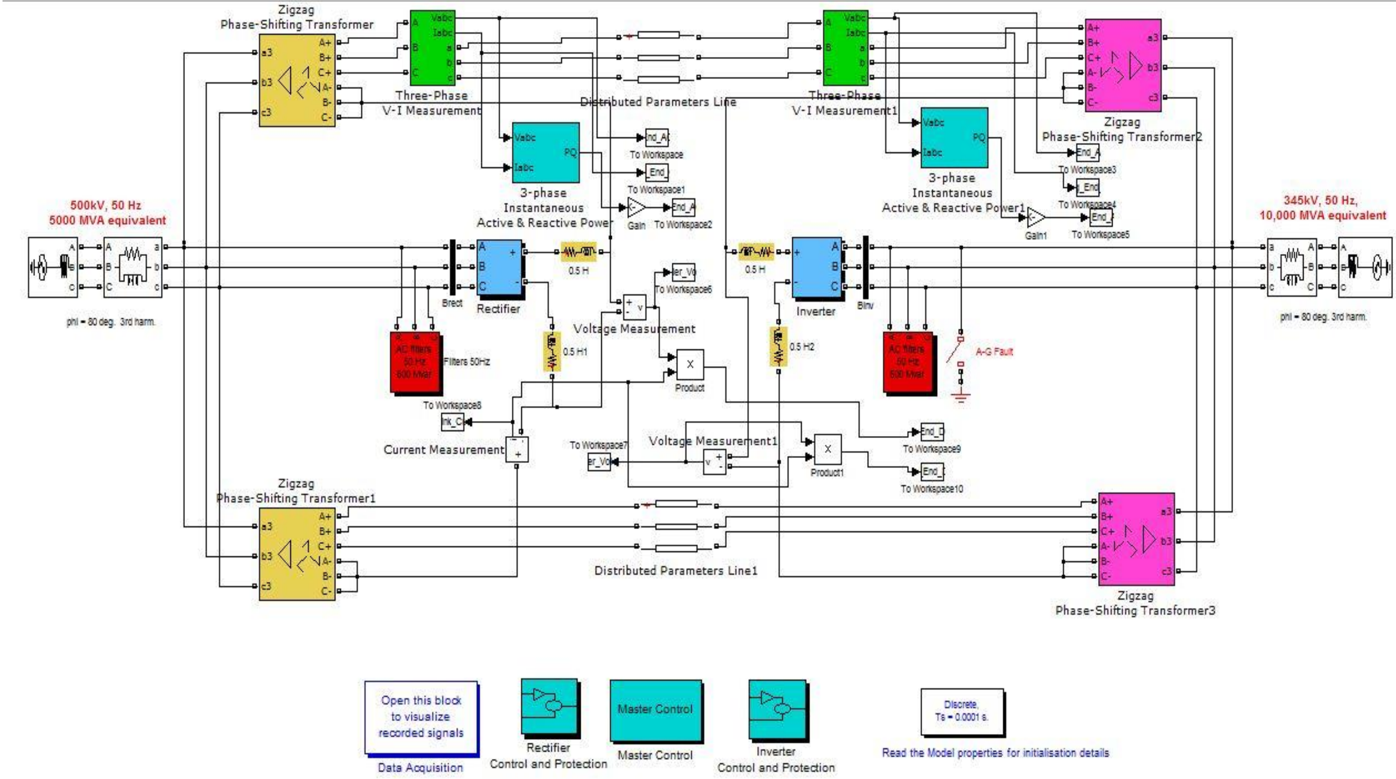


Figure 3: Proposed Simulink Model for Simultaneous AC-DC Power Transmission System

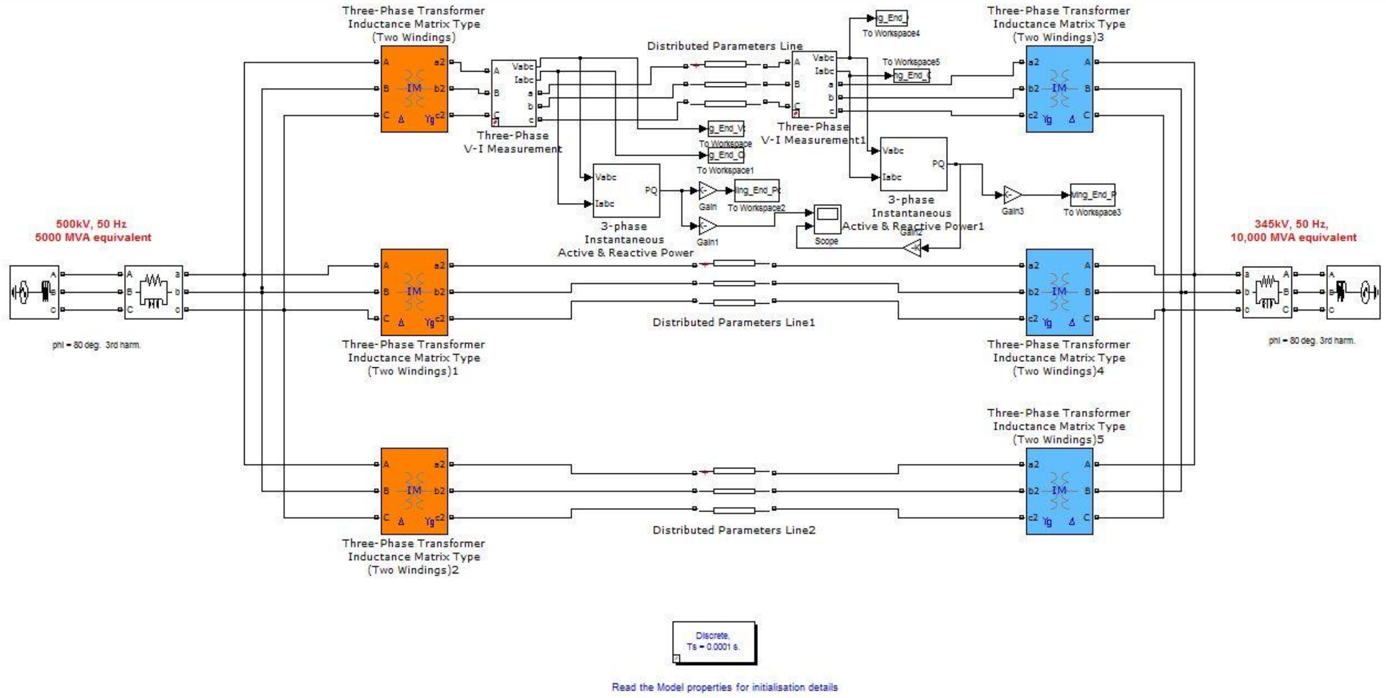


Figure 4: Proposed Simulink Model for EHVAC Power Transmission System

The networks depicted in figures 3 and 4 were studied using MATLAB / SIMULINK. A synchronous machine is feeding power to 400 kV, 50Hz, three phase, 320km line. The synchronous machines are modelled as Sim Power System’s three phase source with internal R-L impedance.

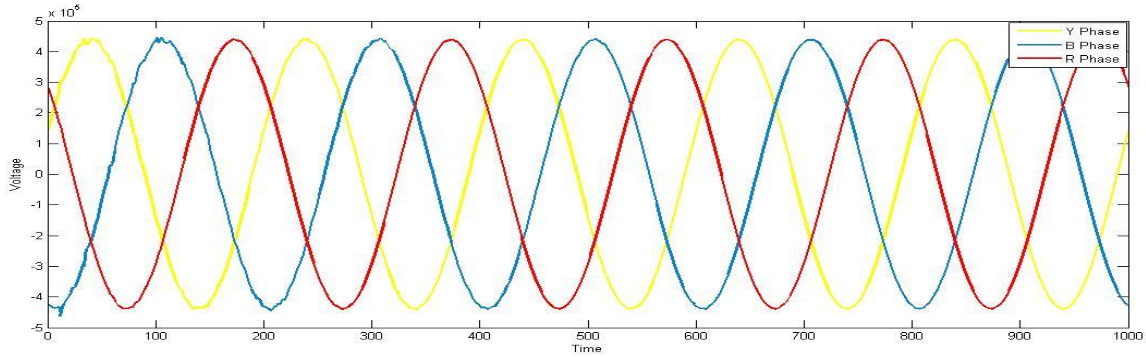
Transmission lines are represented as the Distributed Parameter Line block of Sim Power System. The Distributed Parameter Line block is based on the Bergeron’s Travelling Wave Method. The model consists of inductance and capacitance distributed through its length. The lossless line is characterized by its surge impedance and phase velocity.

The 12-pulse bridge converter and 12-pulse bridge inverter are implemented using two Universal Bridge Blocks connected in series for each converter and inverter. The Universal Bridge Block implements the Graetz Bridge with choice for suitable power electronics devices like IGBT, MOSFET, SCR, and GTO. The twelve pulse operation is achieved by feeding the back to back connected GRAETZ bridges through a three winding transformer with primary winding connected in Y and two secondary windings connected in Δ and Y thus allowing a phase shift of 30^0 in the secondary windings and getting a total of twelve pulses in one cycle (six from each bridge). The rectifier and the inverter control blocks are implemented using Discrete HVDC Controller block of Sim Power System. This block sets the control modes for the rectifier and the inverter respectively. The rectifier usually operates under CC (Constant Current) mode and the inverter works under CEA (Constant Extinction Angle) mode. VDCOL (Voltage Dependent Current Order Limiter) mode works under fault conditions on AC side when there is a large dip in the voltage of rectifier and inverter. This control linearly decreases the current with voltage so as to prevent commutation failure and reduce stress on valves. The firing of thyristors is obtained using Discrete Synchronized 12-Pulse Generator block which obtains its control signal from the Discrete HVDC Controller block. The filter block consists of a capacitor bank, two tuned filters to filter out 11^{th} and 13^{th} harmonics and one high pass filter to filter out higher order harmonics. A master current controller is used to set the current for rectifier and inverter.

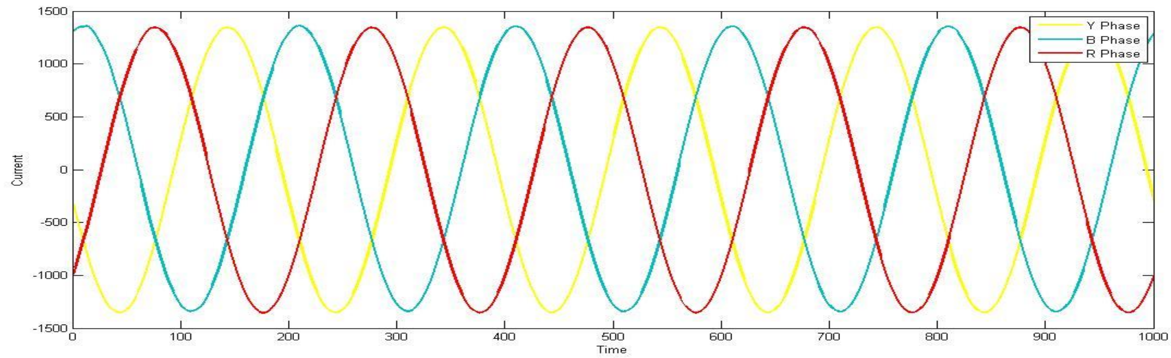
CHAPTER 4

RESULTS

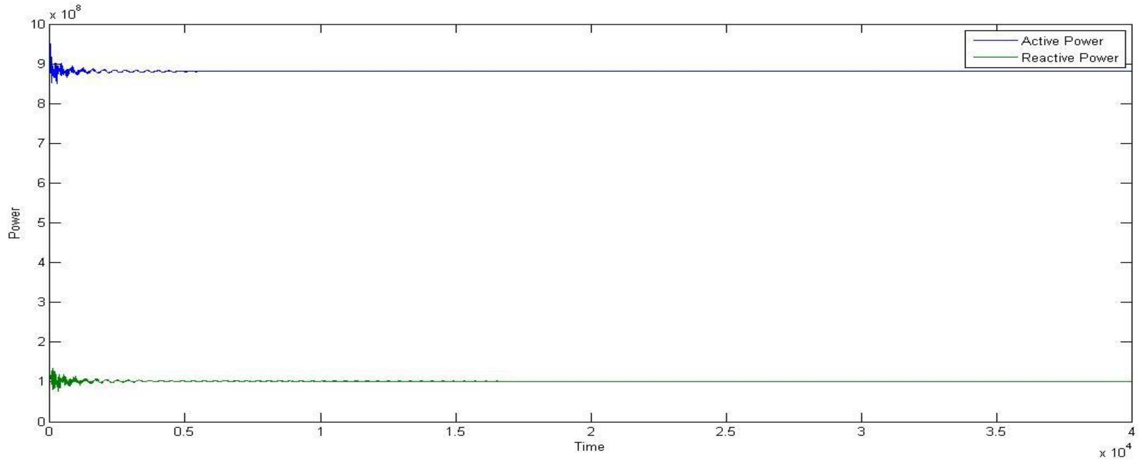
4.1 PURE EHVAC TRANSMISSION SYSTEM



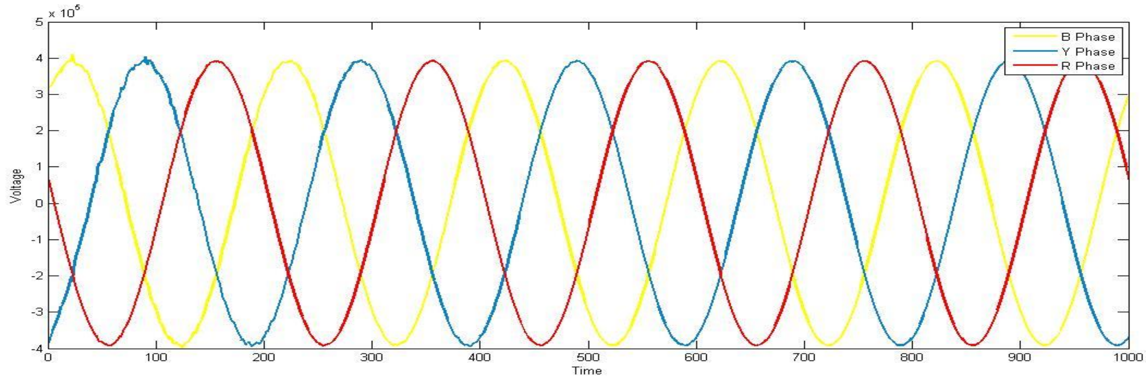
a) Sending End Voltage



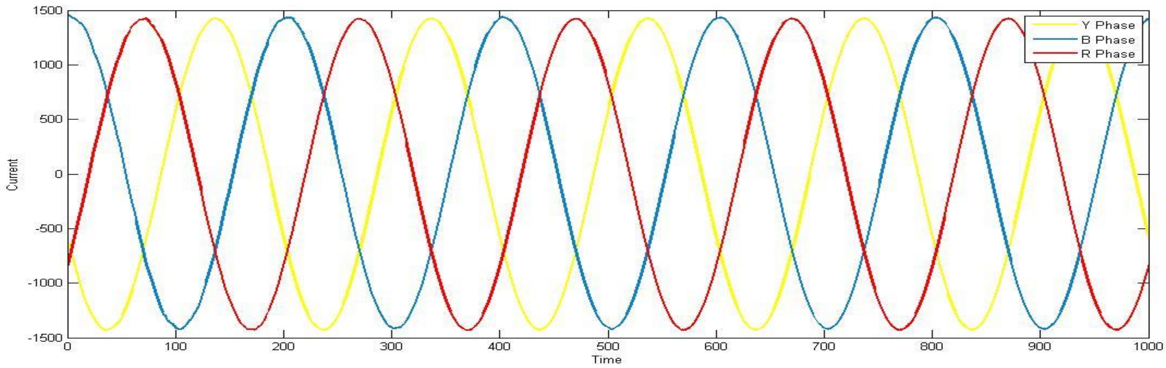
b) Sending End Current



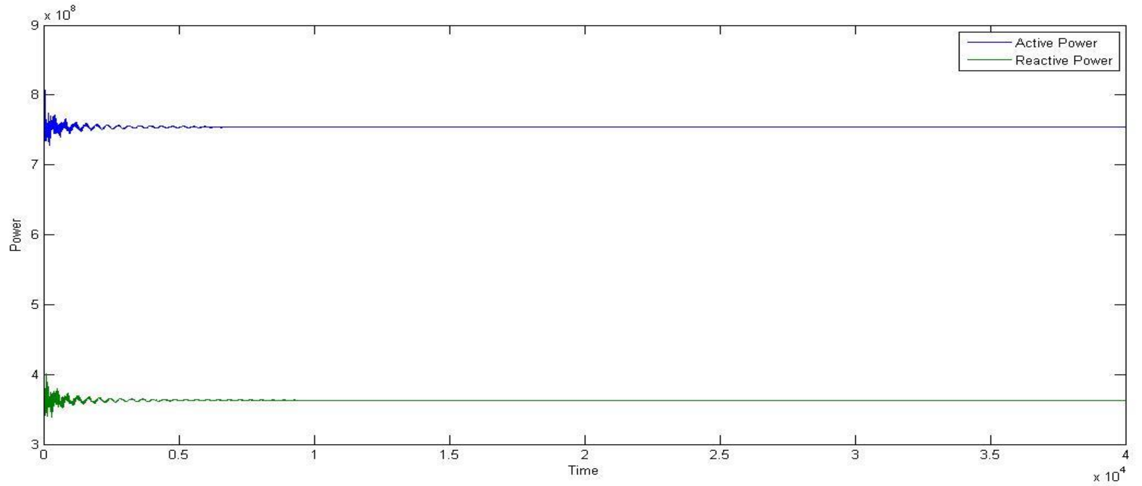
c) Sending End Power



d) Receiving End Voltage

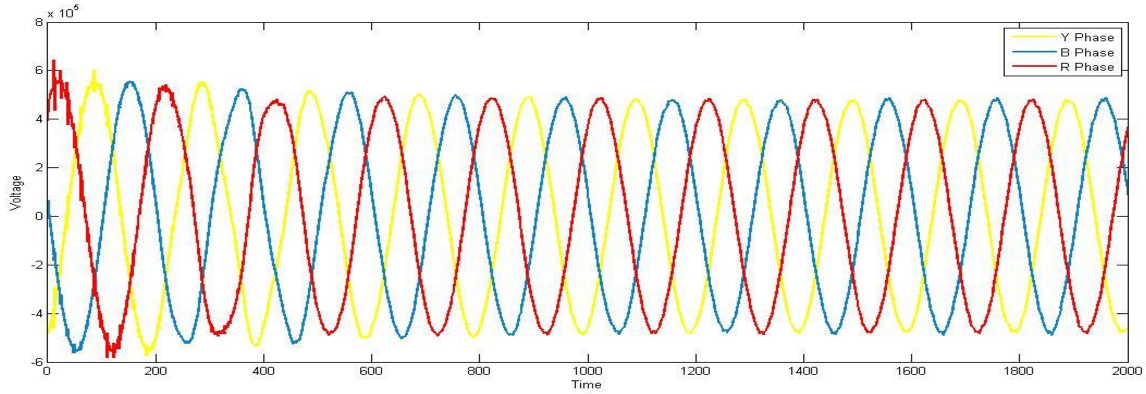


e) Receiving End Current

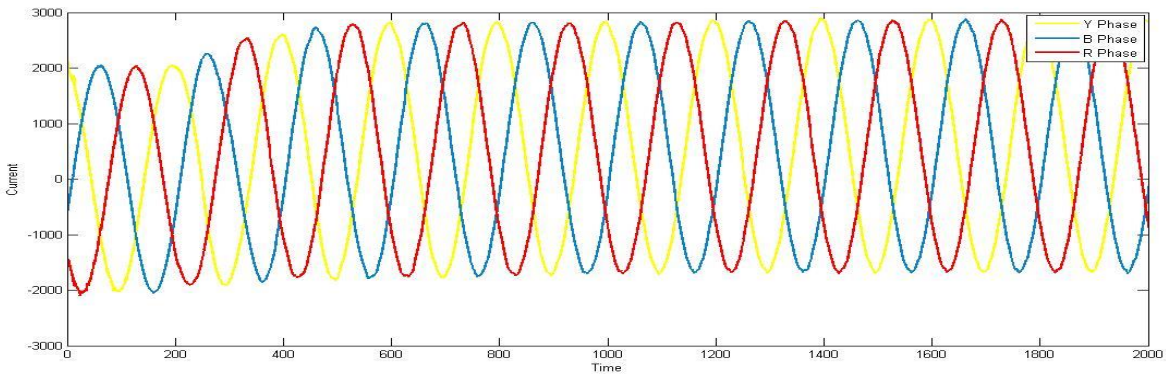


f) Receiving End Power

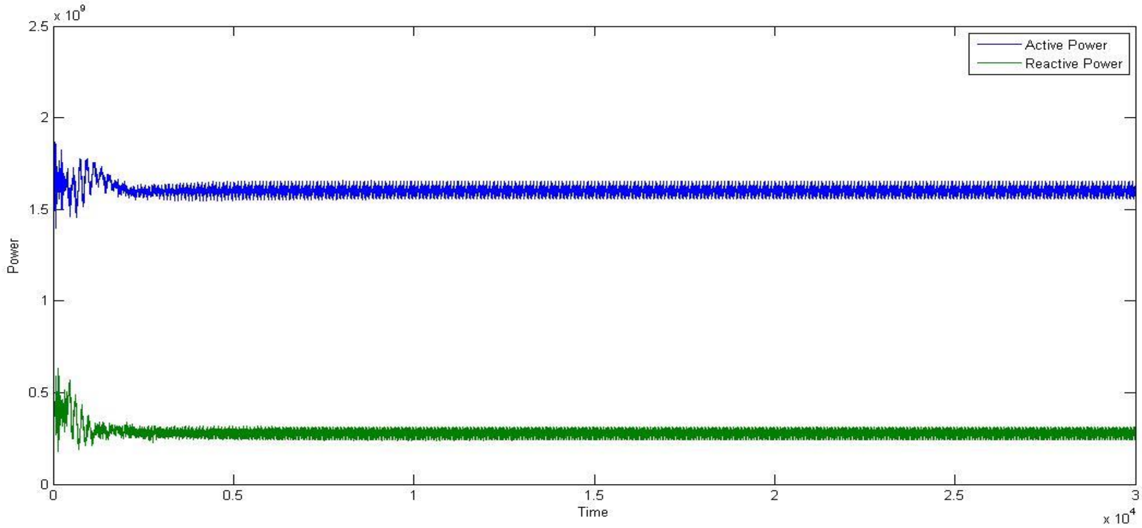
4.2 SIMULTANEOUS AC-DC TRANSMISSION SYSTEM



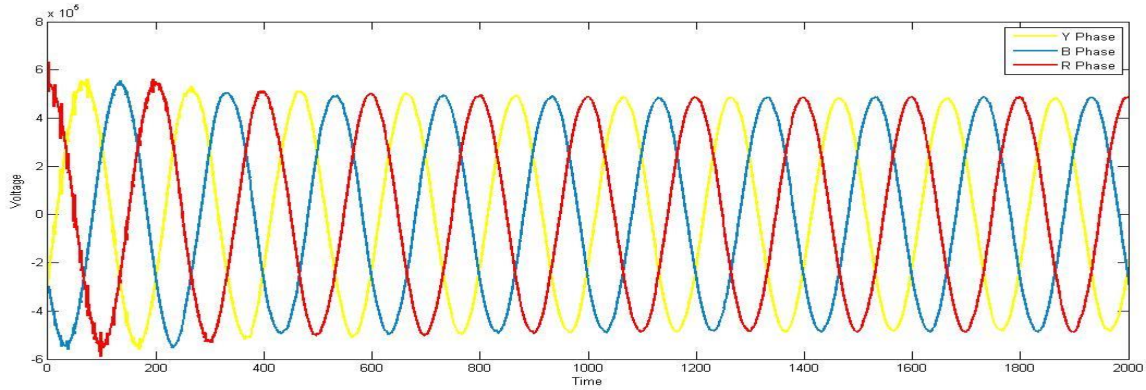
a) Sending End AC Voltage



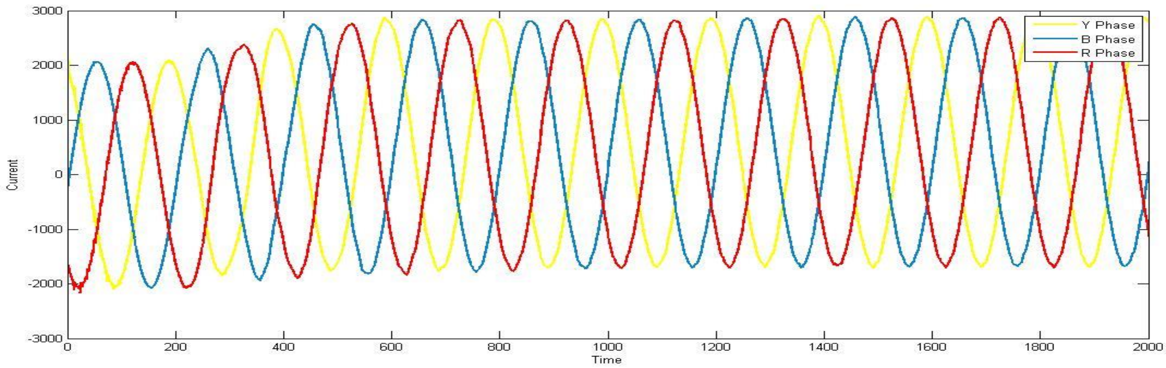
b) Sending End Current



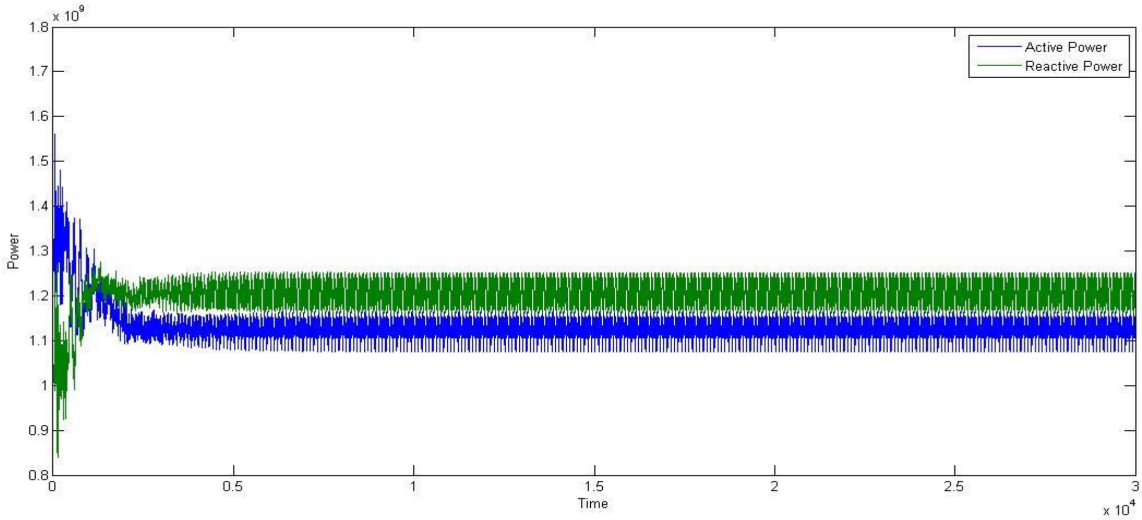
c) Sending End AC Power



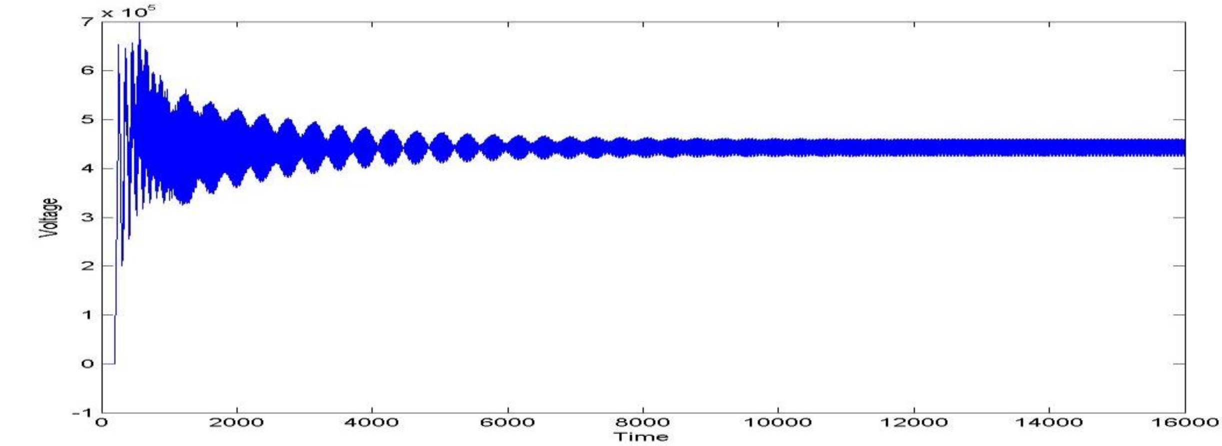
d) Receiving End AC Voltage



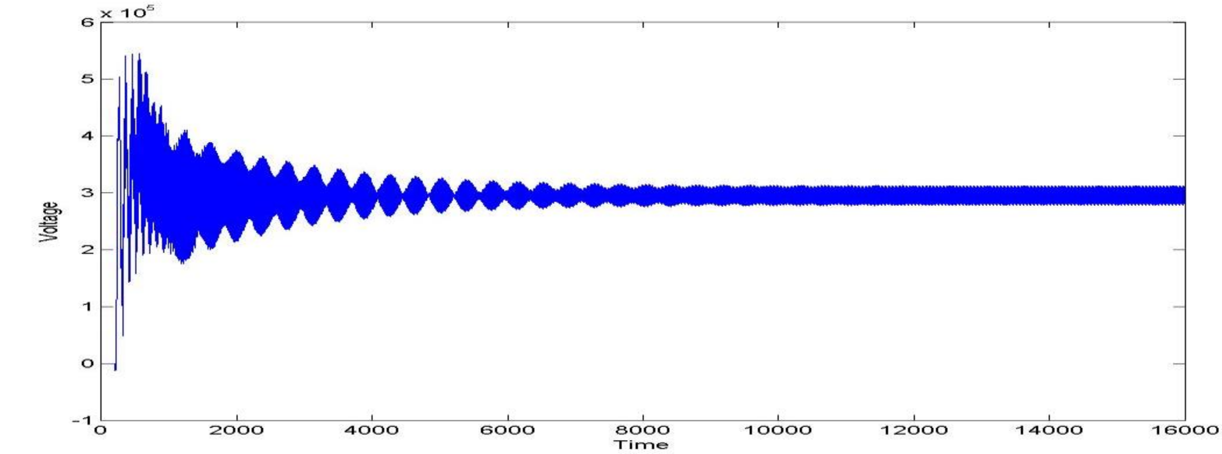
e) Receiving End Current



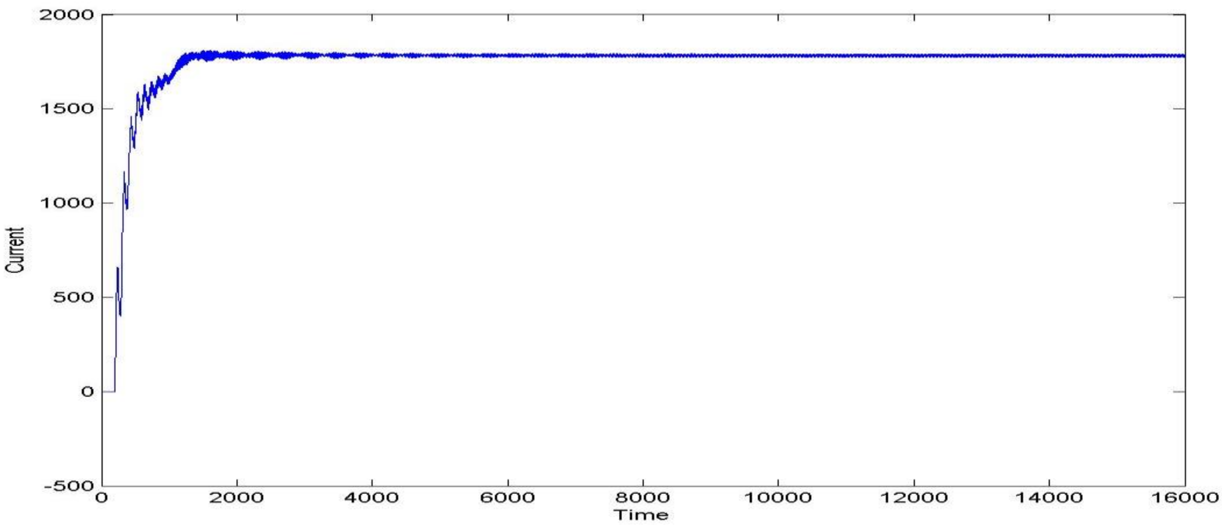
f) Receiving End AC Power



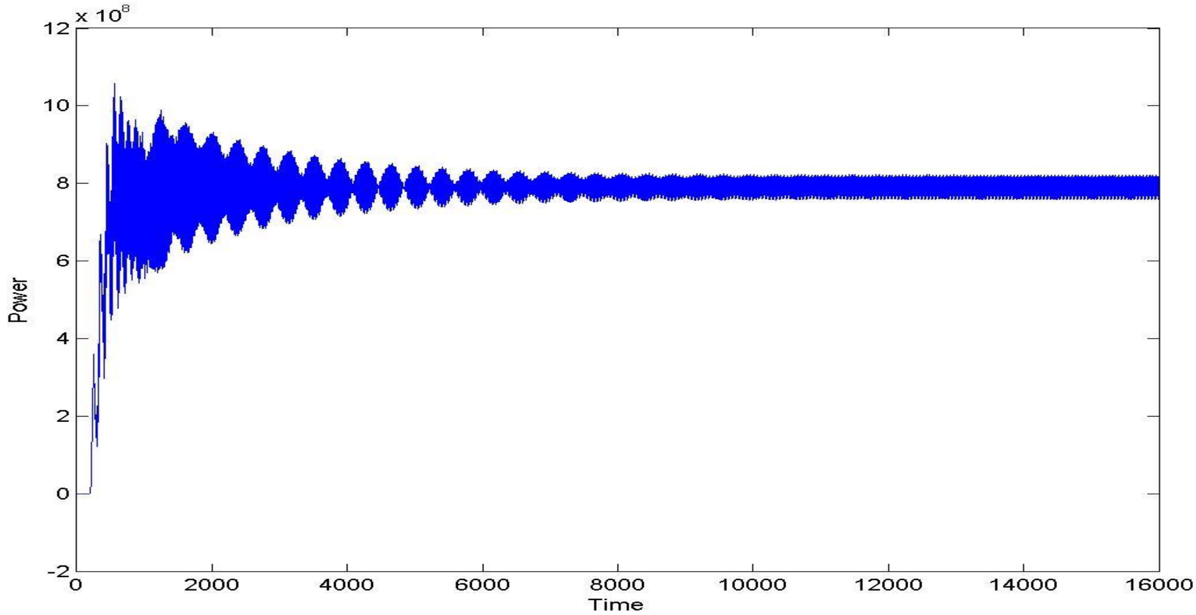
g) Rectifier Voltage



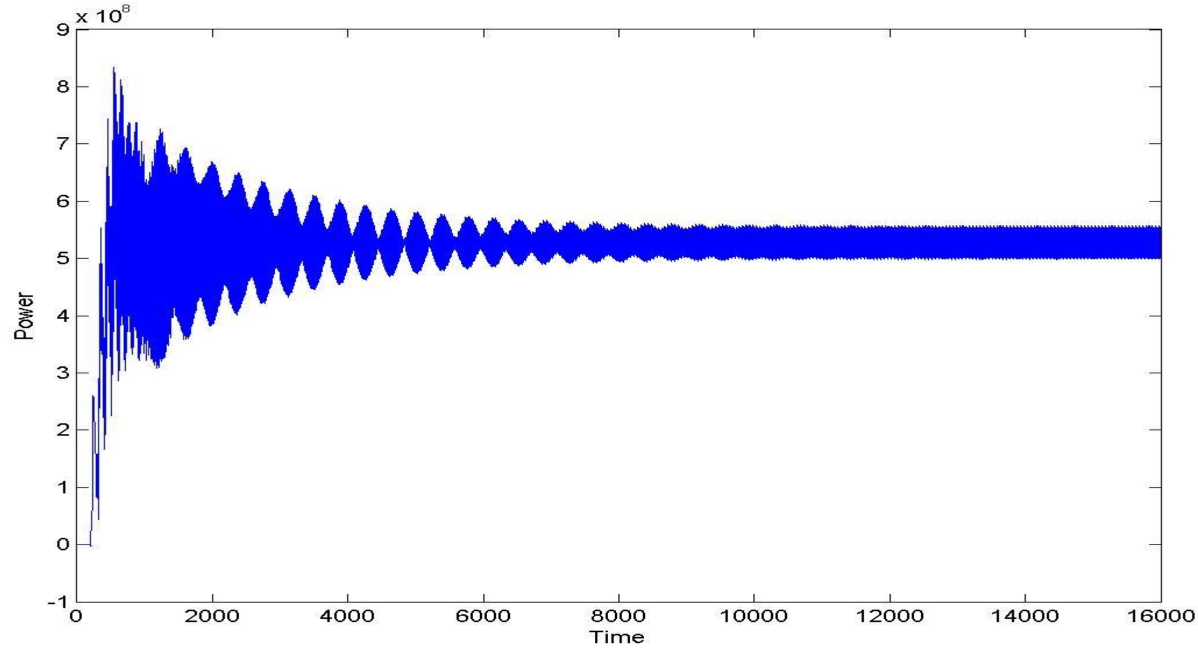
h) Inverter Voltage



i) DC Link Current



j) Sending End DC Power



k) Receiving End DC Power

4.3 COMPUTATION AND SIMULATION RESULTS

AC Line: Twin Moose ACSR Bundled Conductor, 400kV, 50Hz, 320km

Line Parameters:

Resistance per unit length: 0.01273 Ω/km

Inductance per unit length: 0.9337 mH/km

Capacitance per unit length: 12.74 nF/km

4.3.1 Pure AC Transmission System:

Sending End Voltage (V_S) = 400 kV

Receiving End Voltage (V_R) = 392.6 kV

Sending End Power (P_S) = 881 MW

Receiving End Power (P_R) = 750 MW

Sending End Current (I_S) = 952.5 A

Receiving End Current (I_R) = 1004 A

X (Total Reactance per phase per circuit) = $0.9337\times10^{-3}\times320\times314$

= 93.82 Ω

Now,

$P_S = \frac{V_S\times V_R}{X}\sin\delta$

$$=> \frac{400\times392.6}{93.82}\sin\delta = 881$$

$$=> \sin\delta = 0.526$$

$$\therefore \delta = 31.76^0$$

Which is usually the transmission angle in pure AC transmission system as sufficient stability margin is maintained against transient instability.

So, total power transmitted = 3×881 MW

= 2643 MW

Total Power received = 3×750 MW

= 2250 MW

Total Transmission Loss = 2643 MW – 2250 MW

= 393 MW

4.3.2 Simultaneous AC-DC Power Transmission System:

Sending End AC Voltage (V_S) = 400 kV

Receiving End AC Voltage (V_R) = 392.6 kV

AC Current (I_{ac}) = 2.341 kA

Sending End AC Power (P_S) = 1600 MW

Receiving End AC Power (P_R) = 1100 MW

Total Reactance per phase per circuit (X) = 93.82 Ω

Rectifier Voltage (V_{dr}) = 440 kV

Inverter Voltage (V_{di}) = 300 kV

DC Link Current (I_d) = 1.74 kA

Sending End DC Power = 765.6 MW

Receiving End DC Power = 522 MW

Now,

$P_S = \frac{V_S \times V_R}{X} \sin\delta$

$$=> \frac{400 \times 400}{93.82} \sin\delta = 1600$$

$\therefore \delta = 70^0$

Which is usually the transmission angle of a composite AC-DC transmission line as transient stability is greatly enhanced by rapid controllability of DC power.

Total Power Transmitted = 2×1600 + 765.6

= 3965.6 MW

Total Power Received = 2722 MW

Transmission Loss= 3965.6 MW – 2722 MW = 1243.6 MW

Since the rectifier transformer is a three winding transformer with two dc voltage outputs connected back to back, so dc voltage across one winding = 440/2 = 220 kV.

Induced voltage across secondary winding of transformer = 200 kV

So, $V_{dor} = \frac{3\sqrt{2} \times 200}{\pi} = 271$ kV

V_{do} = 220 kV

So, power factor of the rectifier ($\cos\theta_r$) = 220/271 = 0.812

Similarly for inverter

V_{doi} = 271 kV

V_{do} = 150 kV

Power factor of the inverter ($\cos\theta_i$) = 150/271 = 0.5535

So, reactive power drawn by the rectifier = $765.6\tan\theta_r$

= 550.3 MVAR

Reactive power drawn by the inverter = $522\tan\theta_i$

= 785.45 MVAR

Power Upgradation = $\frac{\text{Power transmitted in composite AC−DC transmission} - \text{Power transmitted in pure AC transmission}}{\text{Power transmitted in pure AC transmission}}$

$= \frac{2722-2250}{2250} \times 100$

= 21%

TABLE – I Various Values at Different Transmission Angles

Power Angle (δ)	30^0	45^0	60^0	70^0
AC current I_a (kA)	1.382	1.853	2.18	2.34
DC current I_d (kA)	2	2	1.875	1.74
Conductor current I_c (kA)	1.5344	1.97	2.268	2.41
Sending End AC Power (MW)	870	1220	1470	1600
Sending End DC Power (MW)	1030	960	875	765.6
Receiving End AC Power (MW)	860	1060	1140	1100
Receiving End DC Power (MW)	690	630	575	522
Total Power Transmitted (MW)	1900	2180	3815	3965.6
Total Power Received (MW)	1550	1690	2855	2722
Total Power Loss (MW)	350	490	960	1243.6

CHAPTER 5

CONCLUSION

V. CONCLUSION

The model and technique to convert an ac transmission line into a simultaneous ac-dc line has been demonstrated. For the particular system under study, the power upgradation of the line is observed to be twenty one percent with the simultaneous ac-dc power flow. Maximum power upgradation is obtained at a transmission angle of 60^0. The line is loaded to its thermal limit with the superimposed dc current. The dc power flows independent of the ac power in the transmission line. By using composite ac-dc transmission we can transmit ac power at a transmission angle of around 70^0-80^0 which is generally not possible for a pure EHVAC line. Thus we can see that transient stability of the system is greatly improved by dc power flow which can be rapidly modulated. There is no need for any change in the size of insulator strings, conductors and tower structure of the original line. MATLAB / SIMULINK model verifies the feasibility of simultaneous ac-dc power flow.

REFERENCES:

[1] H Rahman and B H Khan "*Possibility of Power Tapping from Composite AC-DC Transmission Lines"* IEEE Transaction on Power Delivery, Vol. 23, July 2008, pp 1464-1471

[2] Padiyar,"*HVDC Power Transmission System",* New Age International Publishers, New Delhi, 2nd revised edition 2012.

[3] A. Clerici, Paris L. and P. Danfors "*HVDC conversion of HVAC Line to Provide Substantial Power Upgrading*", IEEE transactions on Power Delivery, vo1.1, 1991

[4] L.K. Gyugyi et al., " *The Unified Power Flow Controller; A new approach to Power Transmission Control",* IEEE Transactions on Power Delivery, vol. 10, No. 2, April 1995, pp. 1085-1097.

[5] J. Arillaga and N.R Watson., "*Computer Modelling of Electrical Power Systems*", John Wiley & Sons, England, 2003